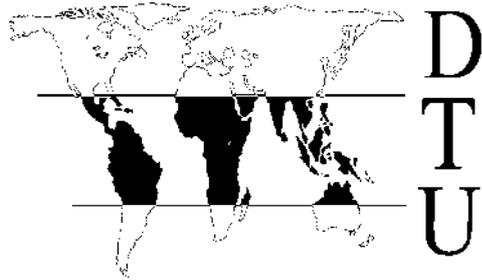


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**Destructive Effects of Moisture on the Long-term
Durability of Stabilised Soil Blocks**

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A.G.Kerali

Development Technology Unit
School of Engineering, University of Warwick
Coventry, CV4 7AL, UK
Tel: +44 (0) 2476 523122 Fax: 1203 41892
email: dtu@eng.warwick.ac.uk
<http://www.eng.warwick.ac.uk/DTU/>

DTU Working Paper 52**February 2000****DESTRUCTIVE EFFECTS OF MOISTURE ON THE LONG TERM DURABILITY OF STABILISED SOIL BLOCKS****by A G Kerali****1. INTRODUCTION**

This working paper describes the summary of the research conducted at the University of Warwick during the 1998/99 academic year. The purpose of the research was to investigate the main mechanisms responsible for the deterioration of compressed stabilised earth blocks, hereinafter referred to as blocks, and to propose remedial measures for their improvement. The scope of the working paper at this stage is limited to the study of the influence of moisture on the durability of blocks.

A working paper describing the influence of moisture on the durability of blocks has been long overdue. A compressed stabilised earth building block may be defined as one formed from a loose mixture of soil and/or fine aggregate, a stabiliser and water in a damp mix which is compressed to form a dense block before the stabiliser hardens (Gooding and Thomas, 1995). After hardening the block should be able to demonstrate higher compressive strengths, better dimensional stability even on wetting and improved durability, than a similar block produced in the same manner but without the addition of the stabiliser. However, since the blocks are produced from soil as the bulk constituent, and given the poor resistance of soil to water, the long term behaviour of the blocks are dependent on the environment and on time (Fitzmaurice, 1958). For this reason, since the introduction of blocks a few decades ago, interest has been growing in understanding the critical factors governing the long-term durability of the material. The durability of blocks is likely to remain a major concern in the foreseeable future. Blocks may be popular and widely used in developing countries, but aggressive environmental conditions such as cyclic changes of moisture content, temperature and pressure over prolonged periods have tended to result in the unexpected shortening of their working life. This has been facilitated either through production shortcomings, or through irreversible changes in the microstructure of the material leading to failure (Tibbets, 1982). This working paper recognises the fact that although in practice several causes of

deterioration may occur simultaneously, with synergy and a cumulative effect, it is nevertheless important to identify the most critical mechanisms, understand the processes involved, and propose remedial measures. This paper suggests that moisture, resulting from driving rains, rising damp, or the condensation of vapour is the most serious factor influencing the deterioration of blocks. If blocks are to become more widely accepted in future as alternative durable building material, then they must be seen to overcome the major drawback of their inability to resist prolonged exposure to moisture (Fitzmaurice, 1958; Agarwal, 1981; Spence and Cook, 1983; Odul, 1984)

The paper examines the experimental work done so far to explain the processes of moisture-linked deterioration. According to literature examined so far, it would appear both that no previous extensive research has been done in this area and that there is a substantial gap in our understanding of the problem. It is hoped that this working paper will contribute towards the orderly progression required to provide a satisfactory theory to assist in understanding the exact nature of the problem, and thereby pave the way for the generation of possible solutions.

The working paper is presented under five main sections namely; introduction, deterioration of blocks, tests and experiments, results and discussions, and conclusion. A list of references used in the preparation of the working paper is presented at the end of the report. Comments, suggestions, and contributions from other researchers, academics, practitioners and users are particularly invited and will be welcome and gratefully acknowledged.

2. DETERIORATION OF BLOCKS

2.1 Basic Wall Characteristics

In order to understand better the deterioration process, it is necessary first of all to appreciate the most important basic wall characteristics. For any new material, it is important to identify, evaluate and understand the basic standard criteria that will be used to analyse the ability of the material to maintain its essential initial qualities (Jennings, Kropp and Scrivener et al, 1994). It is necessary to begin with an evaluation process that will require positive answer to a set of given basic standard criteria. The four key and likely variables to which basic criteria

of assessment could be applied include: relevant material properties, easily measurable properties, initial performance standards for use, and any set durability thresholds during the lifetime of the material (BS CP3 1950; Baker et al, 1994). We therefore seek to answer four questions.

Firstly, what are the primary and secondary properties of the material in relation to the particular application to which it is being designed for? In the case of wall construction for which blocks are produced, the required basic characteristics include strength, dimensional stability, and durability (Spence and Cook, 1983; Carroll, 1992). Important secondary characteristics include weather-proofness, fire resistance, thermal insulation, acoustical insulation and satisfactory appearance (Rigassi, 1995). These wall properties are to a large extent governed by the characteristics of the blocks from which the walls are built (Atkinson, 1970). Good initial block properties are therefore an important consideration in the study of the deterioration of blocks. Secondly, can the relevant properties be measured? Measurement of relevant properties should ideally be possible as and when required. It should be possible to take measurements through immediate tests (surrogate tests) in the case of compliance testing, through medium term tests (accelerated tests) in the case of laboratory experimentation, and through long term performance testing (exposure field tests) in the case of long term performance testing. What numerical limits and thresholds should be attached to the results? Thirdly, do the initial properties of the block fulfil the basic requirements at all in terms of specifications? Fourthly, will the blocks fulfil the requirements during the lifetime of the structure? It is worth noting here that the durability of blocks is closely related to the block properties but are not constant during the lifetime of the block.

It has been suggested in the literature on stabilised blocks that the durability of blocks is closely related to the block properties which in turn are not constant during the lifetime of the block (BS CP 3, 1950; Fitzmaurice, 1958; Atkinson, 1970; Ingles and Metcalf, 1972; Spence, 1975). Despite this potential problem, however, blocks have to be initially strong and remain with adequate strength to carry vertical or lateral loads for the service duration of the wall structure. The blocks have to be durable and weatherproof to exclude any undesirable influences of the environment such as rain, winds, rising damp or other severe weather conditions of exposure. Dimensional stability is necessary to avoid or contain undue volume changes due to expansion or shrinkage. Volume changes, especially under conditions of

restraint such as within a wall structure, often induce undesirable cracks and fissures in walls. These have to be avoided if the service life of the block is to be prolonged.

2.2 Defining Durability and Deterioration.

The terms durability and deterioration are perhaps the two most commonly used words in the field of construction materials. A discussion of what these two words really mean and how they can be assessed in the context of compressed stabilised soil building blocks is necessary for a deeper understanding of the subject.

The underlying assumption driving this research is that durability is probably the most important quality for any construction material since adequate performance over a long time is expected, and implied. According to British Standards, durability is a measure, albeit in an inverse sense, of the rate of deterioration of a material or component (BSI, CP3 1950). For the purposes of this research, durability will be defined as the ‘measure of the ability of the block to endure or sustain its distinctive characteristics of strength, dimensional stability and resistance to weathering under conditions of use for the duration of the service lifetime of the structure’ after Baker et al, 1990. This definition would seem to suggest that the block must be able to maintain satisfactory performance throughout its service lifetime even under the adverse influence of the natural environment. It further suggests that although blocks may initially have suitable and desirable properties, the continued influence of adverse natural environment may alter these properties for the worse. When such alterations lead to substantial failure of the block ahead of, or within its planned lifetime, then the durability of the material can be brought to serious question. Fortunately however, although most construction materials will alter in one way or the other with time, their durability is not always brought to question. This appears to emphasise the fact that durability is not only related to time, but also to the expected function of the material, and conditions of exposure. Conditions of exposure greatly influence the degree of alteration that the block will witness over time.

The alteration process leading to failure may be termed deterioration. The term deterioration will be defined here as ‘the time related loss of quality of the block under the direct or indirect

influence of the environment' (Atkinson, 1970). The term as defined may be used to distinguish failure due to the inability of block to fulfil its basic engineering functions from the alterations and possible eventual failure during the lifetime of the block. This term as defined suggests that durability may be taken to be the ability of the block to resist deterioration. It seems very likely, however, that the durability of the block may not be constant. This suggests that due to deterioration, the durability of the block may change considerably. For example, the water absorption and permeability properties of the block may be directly related to the structure and density of the block. However, the structure and density of the block may alter appreciably due to weathering (deterioration). This alteration may considerably increase the water absorption and permeability levels of the block thus accelerating degradation by softening the loose uncemented matrix of the block, and thereby inducing other degradation mechanisms. In short, deterioration and durability influence each other mutually but negatively (Jennings et al, 1994).

The premature degradation of blocks, and the rate at which this may occur, remain of major concern to most researchers (Hammond, 1973; Uzomaka, 1978). A certain length of time is normally required before deterioration starts. This period may be referred to as the initiation stage, which is later followed by the propagation stage when deterioration is progressing. This suggests that the service life of a block structure could be considered to have an initiation phase and a propagation phase which eventually lead to an unacceptable level of deterioration. The service life of the block is therefore the sum total of the duration of the initiation phase and the propagation phase (Baker et al, 1990).

It should however be pointed out that it is very difficult to define precisely a criterion for unacceptable deterioration. This is because such a level of deterioration may depend on a number of factors such as the nature of the use of the structure, the design and the consequences of failure. In moderate climates, The propagation phase is believed to be short in comparison to with initiation phase and hence the service life can be approximated to the duration of the initiation phase. After the initiation of loss of material, the erosion process might proceed at a rate depending on the degree of exposure of the block surface, the bulk resistance of the block, and the stabiliser type used in the production of the block. There is unfortunately still very little literature and data on the subject since no single long-term studies have been conducted. Several methods may exist for the prediction of the service life

of construction materials. These include estimates based on experience, deductions from the performance of similar materials, accelerated testing, mathematical modelling based on the chemistry and physics of degradation processes, application of reliability and stochastic concepts, and through the use of neural networks (Baker et al, 1990; Jennings et al, 1994; Sjostrom et al, 1996). Despite the existence of all these methods it is still important to note that not all deterioration mechanisms are well understood.

2.3 Mechanisms of Deterioration.

The durability of blocks is affected by both surface and block factors. It is therefore important to understand in each case the source of the action, nature of the action/ reaction, the propagation processes, and the measuring techniques available to quantify their effect on the block over time. The most common influencing mechanisms in the performance of blocks are:

- ◆ Moisture related deterioration- in areas of seasonal, cyclic or continuous alternate wetting and drying which lead to the block retaining sufficiently high amounts of moisture to have deleterious effects. The softening and abrasive action of moisture leads to erosion of exposed surfaces (Fitzmaurice, 1958; Wischmeier 1958; Ingles and Metcalfe, 1973; Lunt, 1980; Stulz and Mukerji, 1988; Ola and Mbata, 1990; Gooding and Thomas, 1995).
- ◆ Temperature changes- in areas of high ambient temperatures causing dimensional changes, which when resisted by restraints of the wall results into splitting, warping, crazing, and cracking. Temperature variations may also induce reversible physical properties like strength, hardness, and rigidity. The retention of moisture and loss through evaporation are dependent on the surrounding temperature. A weakened block then becomes more susceptible to further damage from internal stresses since the maximum load it can carry reduces (Atkinson, 1970; Lunt, 1980; Spence and Cook, 1983)
- ◆ Freezing and thawing-in regions where the environmental conditions allow frost action on exposed blocks under restraints of the wall structure can cause deterioration. The moisture content of the block may near or reach saturation from thawing water or other sources. A

block subjected to repeated cycles of freezing and thawing, coupled with the effect of the ice growth in the voids, and the associated development of both hydraulic and osmotic pressures, result in the build up of expansive forces within the pore system. This leads to disruption, loosening and breakdown of particles (Ingles and Metcalfe, 1973; Houben and Guillaud, 1994)

- ◆ Chemical agents- where present in the soil like sulphates, calcium hydroxide, soluble salts and acids could potentially react or instigate reactions with the cement bonding component in the block. Sulphate attack is common in clayey soils in terrains of high ground water levels containing sulphates. Exposed blocks, which absorb or permit the passage of water or moisture, enable the calcium hydroxide present in the hardened cement mix to be removed by dissolution, a process also known as leaching. Soluble salts such as sulphates and chlorides entering the pores within the blocks and crystallising within the pores may induce internal stresses leading to cracking. Acid attack on the cement element of an exposed block surface leads to direct disintegration of the hydrated cement mix. Chemical attacks may be prevalent where the blocks are used in foundation level applications, but similar attacks have been rare in the case of above ground use of blocks. The presence of moisture in the block facilitates and speeds up most of the chemical reactions (Neville,1986; Houben and Guillaud, 1996; PCA, 1971; PCI, 1970; Spence, 1975)

- ◆ Physical action –mostly occur through adhesive, abrasive, and erosive wear of the block surface, especially the corners and edges. Adhesive wear occurs when two solid surfaces slide against one another under high pressure leading to the removal of material from the surface of the block. Abrasive wear may occur when material is removed from the block surface by contact with, and cutting action of other hard particles. Erosive wear may occur through the impingement and softening action of fast moving liquids leading to loss of material. A block saturated with high levels of moisture over prolonged periods is more susceptible to further damage by physical action (Houben, Rigassi and Garnier, 1996; Lunt, 1980)

- ◆ Volume changes- may take place within the block due to the drying shrinkage, variations in temperature, and moisture variations. When the change in volume is resisted by internal

or external restraints, cracking results. The block is inherently sensitive to moisture variations due to the presence of clay as its constituent component. The determination of the amount and type of clay present in the soil for block production is of paramount importance. The presence of moisture does have the potential to disperse the clay wafers (Scot, 1963; Van Olphen, 1977; Lunt, 1980; Torraca, 1988).

From the above summary list of possible deterioration mechanisms, the direct or indirect presence and action of moisture is a common denominator in influencing the degradation processes. The potential damaging effect of moisture on the long-term performance of blocks could now be recognised as the most critical processes affecting the durability of block structures (Ola and Mbata, 1990; Spence, 1975; Ingles and Metcalf, 1972; ILO, 1987; Houben and Guillaud, 1994). This research paper therefore focuses on attempting to understand the nature of the action of moisture that would for example lead to loss of material from the block. Mass loss is chosen as the performance criteria because it is more amenable to measurement than for instance strength loss, swelling or expansion, and cracking. The theory likely to explain the phenomena satisfactorily will be presented, and experiments that simulate the damaging processes conducted.

2.4 Critical Moisture Action.

As previously noted, changes in the properties of blocks leading to unacceptable levels of deterioration may result from both surface and bulk factors. Weathering through the abrasive and erosive action of moisture often leads to severe loss of material for exposed surfaces of blocks. It is therefore important to identify the sources of moisture, nature of its action, the transport mechanics and the measurable parameters. The inputs that could affect the performance of the block are wide ranging. The most significant of these however include the exposure level to environmental elements (in this case rain) and the manufacturing processes (stabiliser type and content, compaction pressure, clay content and mineralogy, moisture content, curing time, mixing, vibration etc). Both of this result into time varying product properties (density, porosity, permeability, water absorption and retention, etc). The research effort in this case is focused on the examination and quantification of the loss in mass from the block due to the action of moisture from external sources.

Driving rains, rising damp and condensation are the main sources of moisture that could potentially be detrimental to blocks (Torraca, 1988; Agarwal, 1981; Lunt, 1980; Houben and Guillaud, 1994; Norton, 1997). The cyclic wetting and drying of blocks often ensures that there is sufficient moisture to have a decrepitating influence. The durability of the block appears to depend to a great extent on the water absorption capacity, permeability and porosity properties of the block on the one hand, and on the nature of the moisture action, and the capacity of the block to resist disruptive forces on the other. Permeability and porosity appear to play a major role in the entry and retention of pore water, and its mobility inside the block. The actual destructive action of moisture once the block has been penetrated could largely be through adsorption resulting in surface energy changes, dissolution and softening of loose particles, disruption of loose bonds or through pore pressure generation resulting in disruptive internal stresses (Fitzmaurice, 1958; Wischmeier, 1958; Franklin and Chandra, 1972; Ingles, 1972; Darve, 1990). The capacity of the block to resist the disruptive action of moisture will determine the rate and extent to which weakening, softening, swelling, shrinkage, or complete disintegration and loss of material will occur. This analysis would appear to imply that a block which is either impermeable, has a high intergranular strength, and is non-reactive to softening, would be very durable. The question to ask is; given the present fragmented knowledge, can such a block be made? Impermeability and high intergranular strength are directly related to the microstructure of the block, an area rarely covered in stabilised soil literature to date but through which major advances have of recent been made in the improvement of comparable building materials.

According to the literature (Ingles, 1962; Herzog and Mitchel, 1963; Lea, 1976; Houben and Guillaud, 1994), in a compressed cement-stabilised block, the cement binder undergoes a three-phase reaction with the clay component of the soil. This three-phase reaction results into a three matrix mix comprising; an inert sandy matrix bound with cement, a matrix of stabilised clay, and a matrix of unstabilised soil. Assuming that the matrix of unstabilised soil represents the greatest constituent of the block, and yet is also the most vulnerable of three matrices to softening and erosive loss, one would be inclined to predict that the continued exposure of the block to moisture would lead to irreplaceable loss of material from the block over time largely due to the unstabilised matrix.

Other possible mechanisms that may arise from the action of moisture could include ion exchange in the clay minerals, capillary effects, and stress relief (Franklin and Chandra, 1972). Clay bearing blocks are especially susceptible to moisture weakening. Among the several mechanisms that may account for this behaviour, ion exchange appears to be dominant. Clay minerals in the block are surrounded by an atmosphere of adsorbed cations, usually hydroxyl ions that are still loosely bound (Torraca, 1988). The particles can be dispersed in water solution containing negative ions, or can be flocculated by positive ions. The ionic dissociation of the dispersing solution as measured by its dielectric constant controls the efficiency of the dispersion, but the type of clay used also matters. Sodium clays are the easiest to disperse then potassium, magnesium and barium clays. Some clays, for example illite and montmorillonite, contain inter-layer potassium ions that favour hydration. In this instance, the swelling of the crystal lattice may well assist in the dispersion process. Capillary effects, due to the presence of pores in the block microstructure, are likely to play an important part in moisture degradation. Water menisci in the block increase their radius of curvature as the block becomes saturated, so that capillary tensions at grain contacts, and at the tips of cracks are reduced. Also water that is drawn into the block by the action of strong capillary forces may compress entrapped air in its path, resulting in the disruption of the block. Stress relief is probably also an important mechanism, since compressed clay bearing soils subjected to diagenetic forces, are likely to store elastic strains that will be released if intergranular bonds are weakened by the repeated action of water.

In order to quantify the loss of material as a result of the action of moisture, it is necessary to establish a good scientific yardstick of measurement and comparison. There are at present a number of durability tests in use, but with scant application. These include the wet-dry-cycling test, the abrasion test, the rain erosion test, the freeze thaw test, and the immersion test (BSI 4315, 1970; Lunt, 1980; Spence and Cook, 1983; Houben and Guillaud, 1994; Rigassi, 1995). These tests attempt to measure weight loss but cannot be said to measure the resistance of the block to weathering, which is what would be useful. A test is therefore required that would measure the resistance of the block sample to weakening and disintegration resulting from an accelerated abrasion, wetting and drying cycle. The test could be fairly simple, practical, accurate and replicable in application. An index test that would not only measure loss of material but also provide an indication of the comparative degree of

alterability of the block would be more useful. This working paper proposes such a test in Section 3.

3. TESTS AND EXPERIMENTS

3.1 Need For Tests

Stabilised blocks used for external walling have been widely reported in the literature as being prone to deterioration through weathering i.e., softening and erosion leading to loss of mass. The blocks have also been reported to experience lower wet compressive strength and larger dimensional changes than walls made of other comparable masonry materials such as concrete blocks and fired or burnt clay bricks exposed under similar conditions of service (Fitzmaurice, 1958; Lunt, 1980; Spence and Cook, 1983; RILEM, 1987; ILO, 1987; Stulz and Mukerji, 1988; Houben and Guillaud, 1994). The personal experience of the author who built several dwelling units using the same material in East Africa would also add testimony to this premise (Kerali, 1996). The problems have tended to be more serious in tropical upland climates and humid wet climates which experience more seasonal and very intense rainfall than in the more arid hot dry climates (Eaton, 1981; Spence and Cook, 1983; Ola and Mbata, 1990). Prolonged periods of wetness due to continued exposure from double or triple rainy seasons could be of particular concern

Tests and experiments on blocks on blocks are necessary firstly to measure the block properties upon which durability is dependent like strength, water absorption, micro- and macro-structural changes, and secondly to monitor the blocks performance in conditions which simulate the cause of the deterioration. The tests will provide experimental results and data from which general and localised trends could be identified, and from which comparisons can be made with theoretical predictions or other available data. The tests also would provide an opportunity with which the validity of currently held beliefs could be tested, and any agreements or departures from the norm spotted. The literature on stabilised soils still has scanty and/or little information and data on the influence of moisture on the durability of blocks (Gooding, 1995; Spence, 1975). Translating the experimental data into information to facilitate the potential improvement of the durability of blocks would be the broad objective.

3.2 Selection of Tests to be performed

Four separate tests and experiments, all of which have direct bearing with the investigation of the effect of moisture on the durability of blocks, were selected and conducted. The tests include the wet compressive strength test, the water absorption test, the slake durability test, and microstructural analysis of block samples. Although the wet compressive strength test and the water absorption tests are both now standard performance tests widely described and used for stabilised soils, they were originally developed for concrete blocks and fired bricks. The wet compressive strength of blocks has to be known because it is on the value of the wet compressive strength that structural designs are based. The compressive strength values also give an overall picture of the quality of the block and are an indication of the hardness of the hydrated cement paste that binds the various particles together. In most of the climates where the wall will be wet most of the time, it is critical to know the wet compressive strength values for design and compliance purposes. Moisture, it has been stated in several parts of this report, is responsible for most of the damage in blocks. Through the water absorption test, it should be possible to determine the ability and extent to which blocks can absorb moisture. Knowledge of the water absorption levels of blocks could serve as useful criteria for setting limits and for investigating possible ways of reducing the same in order to improve on the durability of blocks. The slake durability test may not yet be a standard test for stabilised soils, but it remains a standard durability test for measuring the resistance of clay bearing rocks to alteration from the accelerated action of moisture (Franklin and Chandra, 1972). The test was adopted for use with blocks in this research because of its several attractions over existing methods such as the wet-dry-cycling test, the abrasion test, the rain erosion resistance test, the freeze thaw test and the immersion test. All existing methods are non-standardised, fragmented and limited in approach, and rely heavily on the operator for results. A test was sought that would be simple, controllable, reproducible, practical, accurate, and reliable. The slake durability test was able to measure not only the loss in mass but also provided some information by way of an index to show the degree of alterability of the block when subjected to controlled cyclic wetting and drying, erosion and abrasion. The test was also easily applied to test concrete block samples and fired brick samples, and the results compared to those obtained from blocks. Interest in examining the microstructural characteristics of blocks, an area not covered anywhere in stabilised block literature,

emanated directly from the results obtained from the standard and adopted tests in an attempt to understand the nature of the distinct phases and the degree of connectivity of the block constituents. The test procedures and operations are presented in the section 3.4.

There are several manufacturing variables that could affect the performance of blocks. These include soil type, cement content, compaction pressure, moisture content, and curing regime (Rigassi, 1995). In the experiments conducted it was decided that of these several variables, only the cement content be varied while all the other parameters would remain fixed. The reason for this decision and approach was based on the fact that it was the stabiliser content which, according to the literature on stabilised soils, was significantly responsible for the improvement in strength, dimensional stability and durability of blocks. Although compaction pressure could contribute towards increasing the densification and thereby reducing voids, it is the stabiliser content that is responsible for binding, sealing, reinforcing and imparting flexibility to the block (Stulz and Mukerji, 1983). By binding the soil particles tightly together, the stabiliser may increase the compressive strength and impact resistance of the block, as well as reducing its tendency to swell and shrink; by sealing all voids and pores and providing a waterproofing film, the stabiliser may prevent or reduce water absorption; by imparting a degree of flexibility which allows the soil to expand and contract within limits, the stabiliser may help to reduce cracking; Conversely, by reinforcing the soil, the stabiliser may reduce excessive expansion and contracting. The effect of stabilisation is greatly increased when the soil is compacted (Ingles and Metcalfe, 1972; Stulz and Mukerji, 1983; Spence and Cook, 1983; Thomas and Gooding, 1995). In the experiments conducted all blocks were compacted prior to curing to a compaction pressure 10 MPa, a value considered to be high enough to produce the best possible quality blocks. In practise however, compaction pressure values much less than 10 MPa are used. In subsequent experiments to follow, both the compaction energy and the cement content will be varied. The stabiliser used in these experiments was ordinary Portland cement conforming to BS 12: 1972. This is because of all known stabilisers currently on the market, it is only ordinary Portland cement which is widely available and used in most parts of the world. It is likely to remain the stabiliser of choice due to its well-established reliability, availability and quality record.

3.3 Specimen Preparation

The preparation of specimens was considered to be one of the most important stages in the execution of the experiments. Extra care had to be taken with the soil, cement mix, moisture content, compression, curing, and sizing of the samples. The high levels of accuracy, reliability and consistency demanded by the experiments be maintained throughout the testing regimes, and for all the different types of tests conducted. Specimen preparation describes the raw materials used, the mix proportions, addition of moisture, the compression method used, the curing regime, and the dimensions of the samples.

For the raw material, an artificial soil for laboratory testing purposes was prepared by mixing ordinary builders sand and potters powder clay of the kaolinite type (grade E). Kaolinite clay was selected for its known non-expansive nature (Craig, 1987; Das, 1983; ILO, 1987; Webb and Lockwood, 1987; Lunt, 1980). Preparing the soil raw material in this way was found to be necessary in order to ensure that the soil mix was a fixed variable for all the different kinds of experiments envisaged. This would also facilitate consistency and repeatability in the research. For purposes of this study, the soil will henceforth be described as 'Soil S'. The proportioning of the ordinary builders sand and the clay powder followed the recommendations obtained from the literature to the effect that an ideal soil would have an optimum raw materials composition of: sand 75%, fines (silt and clay) 25% (Fitzmaurice, 1958; United Nations, 1964). Of the fines, at least not less than 10% has to be clay. The actual mix then used consisted of;

Sand 75%
Silt 13.5%
Clay 11.5%
Total 100.0%

A shrinkage test and a simplified sedimentation test were used to confirm the limits for the different constituents (Houben and Guillaud, 1994). The sand and clay were thoroughly mixed together using the Hobart Machine mixer until a uniform colour was achieved. Proportioning the mix of the soil raw material with the cement stabiliser was done in varying quantities, by percent weight of cement from 3% by weight in 2% increments up to 11% by weight of the soil as follows: 3%, 5%, 7%, 9% and 11%. A total of ten blocks of average

dimension 290x140x100mm were subsequently made in this manner. An extra block, the eleventh, was also produced but without cement stabilisation. For each of the experimental blocks, a fresh mix of the soil S was prepared.

The optimum moisture content was determined, or more precisely, estimated by trial and error (ILO, 1987; Stulz and Mukerji, 1988). To the already prepared soil S mix with cement was added approximately 4% by weight distilled water. The entire mix was left overnight for 24 hours in order to homogenise and get absorbed evenly. After the twenty-four hours, a further 4% to 5% more distilled water was added. To approximate that the optimum moisture content had been near achieved, a drop test was used to ascertain the same (Smith and Webb, ILO/UNIDO Technical Memorandum No. 12, 1987). The constituent parts of the mixed soil preparations were separately weighed using an accurate and sensitive electronic weighing machine to plus or minus 0.05g. To improve on the degree of mix, a mechanical mixer, the Hobart machine, had to be used.

To produce the blocks, a pre-installed BREPAK machine designed on the quasi-static compression principal was used for all the samples. Before filling the mould for each compression, the mould lining was lightly oiled with used engine oil. The soil was carefully poured into the mould in three equal amounts, all pre-weighed, packed and sealed in light transparent plastic bags. After each pouring, the soil was levelled in the mould. The use of the BREPAK machine was based on the operational manual of the machine (Webb and Lockwood, 1987).

The blocks were compressed by the pumping action of the side pump up to 10MPa (517Psi). The machine is equipped with a pressure gauge, which was found useful in confirming the pressure exerted. Each block took approximately 50-60 strokes of the hand pump, as opposed to the recommended 40 in the manual. The last 2-3 strokes of the hand pump however required some exertion. The hydraulic pressure was released using the flow valve screw causing the handpump to become slack. The mould cover was then rotated sideways to expose the green block, which was, then demoulded. The green blocks were then carefully removed using two flat 20mm plywood base plates, and immediately placed in plastic bags and left to cure in the laboratory. The dimensions of the green blocks were recorded and so were the combined weight of the blocks and plywood base plates.

Curing of the blocks consisted of two distinct phases described herein as primary and secondary phases (Webb and Lockwood, 1987). The curing time, temperature, duration, and moisture conditions were of particular interest to the experiment. Primary curing, whose purpose is to ensure that moisture is retained in the block, and not lost rapidly, was done for a period of five days. Laboratory dry conditions were used with curing temperatures of 22-24 C. After the five days, the blocks were noticeably lighter in colour than when demoulded. Each of the blocks were marked using permanent ink markers in each case to clearly show the percentage cement content, moulding pressure, date and time of production, and an identification number (BRE OBN, 1980). This decision to mark individual blocks was to be found very useful later on. In order to enable the blocks to further achieve strength, secondary curing was allowed to continue for a further twenty three days. The clearly marked blocks were placed side by side and covered with a large polythene sheet. This was done to slow down evaporation and to protect the blocks from external interference. The blocks were then left to dry in this manner under laboratory dry conditions.

After a total of twenty-eight days, the blocks were carefully weighed, and demarcated for cutting into smaller 100x100x100mm cubes. The dimensions of the left overs, together with their individual weights, were also taken using callipers and an electronic weighing device. All this information was marked onto each sample individually. The samples were then ready for further testing.

3.4 Tests and Procedures

3.4.1 Compressive Strength Test

The compressive strength of blocks is perhaps their most important property. The main aim of the compressive strength tests was to determine the wet compressive strength values of the blocks. It is the wet compressive strength value, which is normally lower than the dry compressive strength, that is used in the structural design of buildings. The compressive strength test done is a standard test based on BS 6073 Part 1, 1981 and on BS 3921, 1974.

After the 28 days curing period, the blocks of average dimension 290x140x100mm were cut using the concrete lathe machine to reduced cube sizes of approximate dimensions 100x100x100mm. The main compression equipment used was the Denison Concrete Testing Machine 7229/T91081 with a maximum load of 100KN. The machine was certified to grade one calibration for the test duration. Attached to the machine is an automatic electronic input and output recording device. Figure 1 shows a photographic record of the compressive strength test taken during the experiment.

Figure 1. Compressive strength testing of block samples.

Two blocks in each category of varying cement content from 3% in increments of 2% up to 11% were tested for wet compressive strength. Each block sample of dimension 100x100x100mm was soaked for 24 hours or overnight in ordinary tap water. They were then

removed and kept aside for 30 minutes to let the extra surface water to drip off, then capped with two 100x100x20mm thick plywood pieces. The capped samples were then carefully placed within the set marking pins of the compression-testing machine. The crushing load was then continuously applied without shock to the sample at a rate of 15 KN/min till failure, and in this way the maximum crushing load was obtained for each sample. The computerised device of the testing machine then generated all the input and out information namely, reference, sample type, date, time of test, loading rate, sample dimensions and maximum crushing load for each individual test.

The wet compressive strength was then calculated in each case from the ratio of the maximum load and the cross sectional area of the block in N/mm².

3.4.2 Water Absorption Test

The aim of the water absorption test was to determine the percentage moisture absorption capacity of the block samples. Cut block samples were weighed when laboratory dry, immersed in water for 24 hours, removed and weighed again. Samples of concrete blocs and fired bricks were also treated in the same manner and under the same conditions for future comparison purposes. An accurate electronic weighing machine was used in case, to an accuracy of 0.05g. The percentage moisture absorption by weight was calculated from the formula:

$$Mc = \frac{W_w - W_d}{W_d} \times 100 \text{ (\%)}$$

Mc = percentage moisture absorption (%)

W_w= mass of wetted sample (g)

W_d= mass of dry sample (g)

The apparatus consisted of an accurate weighing balance, a stop clock and a water trough with a capacity to hold up to 5 fully immersed blocks (Rigassi, 1995). The entire test took two days to complete mainly due to the overnight soaking of the block samples in water.

3.4.3 Slake Durability Test

The aim of the slake durability test was to provide an index that could help show the degree of alterability of the block samples when subjected to continuous wetting and loss of material through softening and erosion. This is a pioneering test on blocks modified after a similar type of testing regime previously used for clay bearing rocks (Franklin and Chandra, 1972). Samples of concrete blocks and fired bricks were also tested. Figure 2 shows the diagrammatic illustration of the slake durability testing equipment.

Figure 2. Slake durability testing equipment.

The equipment mainly consists of a drum 140mm in diameter and 100mm long with 2mm-sieve mesh forming the cylindrical walls. Four block sample pieces with a combined total weight of between 450-500g were loaded into the drum. The drum was then rotated at 20 revolutions per minute for 10 minutes through a container or more accurately a bath filled with distilled water. After 10 minutes of the slow rotation, some percentage of the block samples were retained inside the drum, while others were dissolved or suspended in the

distilled water filled bath. The block samples were removed, dried overnight in the oven, and then weighed. The slake durability index was then calculated using the formula:

$$SDI = \frac{M_f}{M_i} \times 100$$

SDI= slake durability index (%)

Mf = final mass (g)

Mi = initial mass (g)

After drying, the moisture absorption test was done as before. The test was then repeated for a further 10 minutes cycle, and the slake durability index determined again. The water absorption was also determined again as before for each sample tested.

3.4.4 **Micro-structural Examination.**

Specimen of the block samples made from varying cement content as before and compacted at 10 MPa were examined using the Optical Microscope and screened at magnifications ranging from x10 to x63 (Brandon and Kaplan, 1999). Samples of fired bricks and concrete blocks were also examined in the same manner. The samples which were representative of the whole in terms of features were first observed while in a dry state using the attached binoculars and then their images recorded using the photographic high speed and high resolution cameras also attached to the equipment. The exercise was repeated for the same samples after overnight soaking in water till saturation.

The ultimate good resolution of the recorded pictures was a result of careful sample preparation, imaging in the optical microscope, and individual recording. The optical microscope was selected for the examination of the microstructure because the visual impact of the magnified image would be immediate, and the interpretation of the spatial relationship of the phases would be familiar even to the casual observer. Of major interest to were the inhomogeneity i.e., spatial variation in features and their distribution and the morphological anisotropy of the samples i.e., orientation variations. Since the literature on stabilised soils does not mention any previous work done in investigating the microstructure of blocks by any

of the researchers whose works have been assessed so far, it would be reasonable to state that this test has been a pioneering and pace setting contribution to knowledge. The results are presented in Appendix I, and discussed in Section 4 of this report.

4 RESULTS AND DISCUSSION

4.3 Wet Compressive Strength

The results of the 28-day wet compressive strength values obtained are presented in a tabulated form in Appendix A and in a graphical form in Appendix D. From these results general and localised trends can be discerned.

According to the tabulated results in Appendix A, it would be reasonable to predict that for a given constant compaction pressure, an increase in absolute wet compressive strength can be achieved by increasing the cement content. From the graphical presentation of the results shown in Appendix D, the rate of increase in strength can be approximated. The graph reveals that the absolute increase in wet compressive strength appears to remain constant but then increases less at the lower cement contents but more at the higher cement contents. For instance, when the cement content is doubled from 3% to 6% at constant compaction pressure, a wet compressive strength increase of 130% is achieved; further doubling of the cement content from 6% to 12% would produce a projected increase in wet compressive strength of up to 145%.

The results also show that all the blocks produced at the varying cement contents from 3% in increments of 2% up to 11% but at constant compressive pressure of 10MPa, have 28-day wet compressive strength values well above most of the recommended minimum values for use in structural work. According to the literature, several different values of 28-day wet compressive strength, all above 1.0 MPa are proposed; 1.2Mpa (Houben, Rigassi and Garnier, 1996), 1.4 MPa (Lunt, 1980), 1.0MPa to 2.8 Mpa (ILO, 1987). According to the

1987 ILO Report, the 1.0 MPa 28-days minimum wet compressive strength values are recommended for dry arid zones while the 2.8 MPa minimum 28-day wet compressive strength values are recommended for the wet rainy zones. The high wet compressive strength values obtained in the tests can be explained by the use of a high compressive pressure of 10MPa, which was used to produce the blocks. In practice, however, compressive pressures of less than 10 MPa are adequate.

The behaviour of the block samples tested for wet compressive strength showed that although blocks may be considered as hard and rigid materials, they remain brittle and fragile under the action of extreme loading. The most notable visual observation made during the tests was the fact that damage tended to start from the block edge and corners, and extend to the centre and inner parts. It would also appear from the tests that if the load were removed, the samples would not fully recover their initial shape and configuration. This appears to suggest that blocks are not elastic but could be plastic from their behaviour on removal of the stress. The explanation for this could stem from the fact that blocks are heterogeneous materials composed of many different crystals and particles, held together through contacts and joints with variable degrees of strength. Some of the joints or particles start to break up well before others, causing irreversible deformations that remain even after the removal of the stress.

4.4 Water Absorption

The experimental results of the water absorption test are tabulated in Appendix B, and shown in a graphical form in Appendix E and Appendix F. Appendix E shows the effect of cement content increase on the water absorption capacity of the block. Appendix F shows the effect of bulk density increase on the water absorption property of blocks.

According to the tabulated results in Appendix B, the 28 day mean water absorption values for the various samples tested range from 5.3% for the 11% cement content samples to 8.1% for the 3% cement content samples. The recommended maximum water absorption value is 15% (ILO, 1987). Houben, Riggassi, and Garnier, 1996 proposed the maximum value of 20% water absorption for blocks. During the same test, samples of fired bricks and concrete blocks were also examined for purposes of comparison. The results, also shown tabulated in

Appendix B, reveal mean water absorption values of 9.1% and 3.4% for the fired brick samples and concrete block samples respectively. These results appear to suggest that blocks compacted at 10MPa but with varying cement contents from 3% to 11% have water absorption values which fall within the recommended limits, and which compare well with water absorption values of similar materials like concrete bricks and fired bricks. The fired brick samples actually absorb more water than any of the block samples tested. Does this mean fired bricks are more porous than blocks? Do fired bricks have more voids than blocks? Are the voids more interconnected? Are the values obtained significant in any way for blocks? Why do the fired bricks absorb more water yet are considered to be more rigid and durable? An investigation of the microstructure of blocks and comparable materials is called for. The issues to be determined include the interconnectivity of the pores, the pore size distribution and the total porosity. The results do show that in ambient conditions, the blocks do have a potential to retain significant amounts of moisture.

According to Appendix E, an increase in cement content has the effect of reducing the water absorption value of the blocks produced at constant compaction pressure. A doubling of the cement content from 3% to 6% results into a reduction in mean water absorption of 22%. A further doubling of cement content from 6% to 12% is projected to reduce the mean water absorption by 15%. This shows that the increase in cement content results into a reduction in water absorption, and the reduction is more at the lower cement contents but less at the higher cement contents, eventually becoming constant above the 9% cement content level.

According to Appendix F, an increase in bulk density from 2055Kg/m³ (3% cement content) to 2082Kg/m³ (11% cement content) results into a reduction of water absorption of up to 35%. Above the 2079Kg/m³ density value (9% cement content), any further increase in cement content does not correspond to any further reduction in water absorption. Below the 5% cement content level, an increase in density from 2055Kg/m³ (3% cement content) to 2060 Kg/m³ (4% cement content) results into a reduction in water absorption of 20%. Above the 5% cement content level, an increase in density from 2065Kg/m³ (6% cement content) to 2067Kg/m³ (7% cement content) results into a reduction in water absorption of 2%. Further incremental increase in cement content would result into no further reduction in water absorption. This appears to suggest that a further increase in density would not necessarily

eliminate water absorption by the block. The block would still be able to absorb significant amounts of moisture.

In practice, water can gain access to the block either in liquid phase in the case of rainwater infiltration or suction from a wet surface, or in the vapour phase in the case of condensation or adsorption, but leaves the block almost exclusively in the vapour phase through evaporation. Therefore the water content of the wall should be determined not only by its contact to water sources but also with its water vapour balance i.e., evaporation minus condensation and adsorption. Given that the block undergoes a seasonal cycle with maximum water content in the rainy season and minimum water content in the dry season, such cycles constitute an added complexity in analysing the moisture balance and therefore any remedial steps that could be taken. Would plastering the wall, which in effect hinders evaporation, be useful or harmful? It would be recommended that a test of moisture conditions should follow the entire wet- dry cycle, and be repeated annually. There is currently no known test in stabilised soil literature that corresponds to this. Further studies will need to be conducted in this area as well as in respect of water penetration, mobility, retention and solubility of constituents.

4.5 Slake Durability Test Results

The results of the slake durability test are tabulated in Appendix C, and shown in graphical form in Appendix G and Appendix H.

According to the tabulated results in Appendix C, the mass loss in blocks stabilised with varying cement contents from 3% cement content to 11% cement content ranged from 37% to 7% respectively. Fired brick samples and concrete block samples were similarly tested with results showing mean mass losses of 1% and 4% respectively. This shows that despite the significant water absorption capacity of the fired brick and the concrete block, the integrity of the two materials when subjected to alternate wetting and abrasion, were upheld. One of the three fired brick samples showed integrity of 100% against wetting and abrasion. Does the answer to integrity lie in strong interparticle bonding? Blocks stabilised at 11% and 9% cement content experienced mass losses of less than 10%. Blocks stabilised at 7% and 5%

cement content experienced mass losses of below 20%. Blocks stabilised below the 5% cement content level experienced mass losses of between 21% and 37%. Recommendations encountered in the literature for acceptable limits of mass loss set the maximum at 10% (Spence and Cook, 1983; Fitzmaurice, 1958). Apart from these two references there appears to be complete silence to the possibility and degree of mass losses in blocks. The most significant aspect of this experiment, which attempted to simulate the combined effect of accelerated wetting, softening and abrasion of blocks, was to confirm that blocks do indeed lose mass faster than comparable materials. The answer to redressing this potential problem would probably lie in understanding the degree of bonding, sealing, flexibility and reinforcement capacity of the binder and the contribution of compaction pressure. Why is the integrity of the fired brick, which absorbs more water than the blocks, almost total? The microstructure of the two materials will need close examination if the shortcoming is to be solved. Therein could lie the key to the strengthening of the inter-particle bonds in blocks while continuing to expose them to moist conditions and thereby increase their desirability in the developing countries.

The general trend shown by the results plotted in Appendix G is that an increase in cement content would result into a reduction of mass loss. A doubling of the cement content from 3% to 6% results into a mean reduction in mass loss of 62%. Further doubling of the cement content from 6% to 12 % results into reduction in mass loss of 57%, i.e. only 5% improvement. By extrapolation, would higher cement content of above 15% approximate a zero mass loss? Would further cycles of the slake durability test result into further disintegration of blocks? After how many cycles would the mass loss become constant, or would a weakened block disintegrate?

As with the case of wet compressive strength, it is possible to relate mass loss variation to density variation, with the latter depending mostly on the cement content variation. According to Appendix H, the general trend that emerged showed that an increase in density from 2055Kg/m³ (cement content 3%) to 2063Kg/m³ resulted into reduction in mass loss of 54%. A further increase in density from 2063 Kg/m³ (cement content 5%) to 2067 Kg/m³ (7% cement content) resulted into a lesser reduction in mass loss of 30%. Does this suggest that the higher the density i.e., the lesser the voids, the lesser the mass loss? At a density of above 2085Kg/m³, approaching the zero voids line, would the mass loss be nil? Would it be

possible to achieve this through better processing methods like more vibration before compaction? This aspect, together with the microstructural nature of blocks, will need further investigation.

From the results of these experiments, the slake durability test which combines wetting and abrasion of blocks has the advantage of allowing fast comparisons to be made between blocks made from the same batch, different batches and even different materials to be compared efficiently and reliably. Unlike other durability tests that rely heavily on the actions and senses of the operator, the slake durability test was found to be simple, practical, reproducible, controllable and repeatable.

Among the various factors that could influence the results, the following could be of importance; the apparatus (sieve, drum size, speed of rotation), the sample (size, shape, weight, microstructure, and storage, drying), duration of slaking, nature of the slaking liquid (chemistry and temperature). All these factors are common to most standard tests but could be simplified and adopted. The need to develop a classification of block methods that are quantitative and independent of block dimensions is long overdue. No previous durability tests done in the past have been able to achieve the degree of reliability and controllability made possible through the slake durability test.

4.6 Microstructural Characterisation

The photographic records of the microstructural investigation of blocks and samples of fired bricks and concrete blocks are presented in Appendix I and Appendix J.

According to the images in Appendix I which show the microstructure of a wet block sample and that of a dry block sample both stabilised with 5% cement content, the volume fraction of voids appear quite prominent. In the wet block sample, films of water, which have filled the pores, are evident. The interparticle bond appears to be basically light contact bonds possibly with weak connectivity. It is difficult at this stage, without the benefit of further tests, to discern the distinct different constituents of the block microstructure, such as clay and cement. The larger particles that are visibly prominent due to relative size could be sand particles. What this apparent weakness in bonding and connectivity have on strength may not

be possible to discern at the moment but their implications on softening, dissolution and disintegration could be serious. This is a pioneering investigation in as far as research on stabilised soils is concerned. This investigation also has the potential of revealing contamination or unwanted inclusions in block samples due to inadequate processing techniques. The fact that the wet samples reveal complete saturation with absorbed moisture could have a bearing on the future performance of blocks. Would it be possible to devise processing methods that can reduce the level of the presence of moisture in blocks? Would it be possible to establish relative quantities of the three mixed constituents comprising the block namely, the inert sandy matrix bound with cement, the matrix of stabilised clay and the matrix of unstabilised soil? Which of these three matrices is more prone to softening, dissolution, and erosion? Does stabilisation affect all the sand particles? Further research is required in all these areas. The literature on stabilised soils does not cover these pertinent and critical questions.

The fired brick samples and the concrete block samples appear to have exceptionally high degree of connectivity, almost approximating strong covalent bonding. In the fired brick sample, the clay crystals appear to have melted into a continuous mullite and quartz structure. A hard and non-crystal porous mass appears to have been formed. It would be reasonable to suggest that the higher the firing temperature, the stronger the brick formed. The recommended wet compressive strength of fired bricks is in the order of 5.2 MPa (BS 3921, 1974). The concrete block sample reveals a hard porous but brittle material. The degree of connectivity of the constituent particles also appears to be much stronger than in comparable stabilised blocks. The recommended wet compressive strength of concrete blocks is 2.8 MPa (BS 2028, 1968).

The limitations of this investigation could arise from the fact that the samples used were not as flat and coated as would have been required. No chemical etchants solvents or differential imaging agents were used. The focusing of the images also relied on the use of the eye before imaging. Nevertheless, reasonably good images discernible to the casual observer were obtained. Future research into the differentiation and separation of the different phases that could offer a quantitative approximation of the different constituents should be done.

5 CONCLUSION

The conclusions that could be made from the results of these exploratory tests and experiments are wide ranging, and include;

- ◆ The wet compressive strength of a block is a valuable indicator of its quality, and by implication, its durability. Increase in cement content results in an increase in the wet compressive strength value of blocks made at the same constant compaction pressure. The increase in absolute strength remains constant but increasing less at the lower cement content levels but more at the higher cement content levels. Increase in cement content could be a more effective method of increasing wet compressive strength values, and by implication the durability of blocks than an increase in compaction pressure. The final wet strength reached by a block is much more sensitive to variations in the cement content than to densification.
- ◆ The moisture absorption capacity of the block could be significantly correlated to its durability. Increase in the cement content of block results into a reduction of its water absorption capacity. Further progressive increase in cement content beyond about 9% however only results into a reduced but constant water absorption by the block. The water absorption value of a block reduces with an increase in density, but a further increase in density results into a constant water absorption value. The ability of the block to expel moisture should also be studied in trying to arrive at the moisture balance of the block, and in analysing its potential damaging effects.
- ◆ Blocks made with the highest possible standards of manufacture can still be capable of absorbing water and losing mass when subjected to continued wetting and drying, and therefore softening and erosion. Current durability tests are fragmented, non-controllable and hardly reproducible. A standardised test that can approximate the action of wetting, drying and abrasion is required. An increase in cement content results in a reduction in mass loss, but the least depreciation of blocks would require cement contents approaching 15%. This would be highly uneconomical, so more stringent durability thresholds are needed for lower cement contents especially in wet areas of use. A quick predictive durability test has not yet been developed for blocks.

- ◆ The microstructural characterisation of block samples revealed the presence of a large volume fraction of voids, which could be detrimental to the durability of blocks. The characterisation of blocks in this manner could be of tremendous potential in essaying to understand the nature and degree of bonding of the particles inside the block. Its use could be further extended to analyse the strength of interparticle bonding and/or inter phase connectivity in blocks.

Deliberate further research will still be needed to test refine and validate the findings contained in this report with a view to developing a reliable long-term durability model. Improvements to the durability of blocks can only become possible when most of the currently unanswered questions are settled. The most probable likely answer will lie in ways to achieve higher interparticle bonding and the exclusion of the damaging effects of moisture. Comments and contributions to any aspect and findings of the research report are invited.